TD-01-001
January 6, 2000

MECHANICAL AND THERMAL ANALYSES OF THE CABLE/ STRAND STRAIN TEST FIXTURE

Michela Fratini, Emanuela Barzi

Abstract:

A fixture to assess the superconducting performance of a reacted Nb_3Sn cable under compression by testing the critical current of its single Nb_3Sn strand components was designed and analyzed under the mechanical and thermal points of view. This device was designed to provide V-I measurements in liquid helium at 4.2 K and in transverse magnetic fields up to 15 T. A cable sample is compressed between two plates. A hydraulic cylinder mounted on the top flange of the device allows applying a pressure up to 200 MPa to the cable sample. The copper leads conveying the current to the sample can carry up to 2000 A.

1. INTRODUCTION

During magnet fabrication and operation the critical current, I_c, of a Nb_3Sn virgin strand is reduced due to various factors. In the wind and react technique both strand deformation during cabling (before reaction) and cable compression in the coil (after reaction, due to coil precompression and Lorenz force) contribute to I_c degradation. This latter factor is due to J_c sensitivity of Nb_3Sn to strain. In the react and wind method, there is also to take into account the degradation due to the bending strain introduced during winding.

So far, the Short Sample Test Facility (SSTF) at the TD has allowed measuring the I_c degradation due to cabling of Nb_3Sn strands made with different technologies. These strands were extracted from series of Rutherford cables covering a packing factor range of 85 to 95%, heat treated and subsequently tested [1]. A method was also developed and used to measure I_c degradation caused by bending strains of $\pm$0.2 and $\pm$0.4% in strands of various diameters [2]. Recent I_c data obtained in cable tests have shown an excellent correlation with strand measurements both in the case of unbent -representative of cabling degradation only- and bent samples -inclusive of both cabling and bending strain degradation [3].

The device herein described was designed [4] to provide quantitative information on the I_c degradation occurring under stress in a Nb_3Sn superconducting magnet in the simplest and cheapest way, *i.e.* with strand tests as opposed to cable tests and by using at most the existent facility [5]. To simulate at best the real conditions, in which the superconductor will operate in the magnet, the pressure will be applied to the strand without removing it from the original cable. Cable samples will be insulated, stacked together and impregnated in order to improve pressure distribution.

2. CONCEPTUAL DESIGN

The specifications required by the device were the following:

- Applicable pressure on the sample as high as 200 MPa (20 ton load) to simulate the real operating conditions of the superconducting cable in the magnet;
- Current leads that could carry 2000 A to the sample;
- An available clearance in the solenoid bore of the SSTF of only 64 mm in diameter.

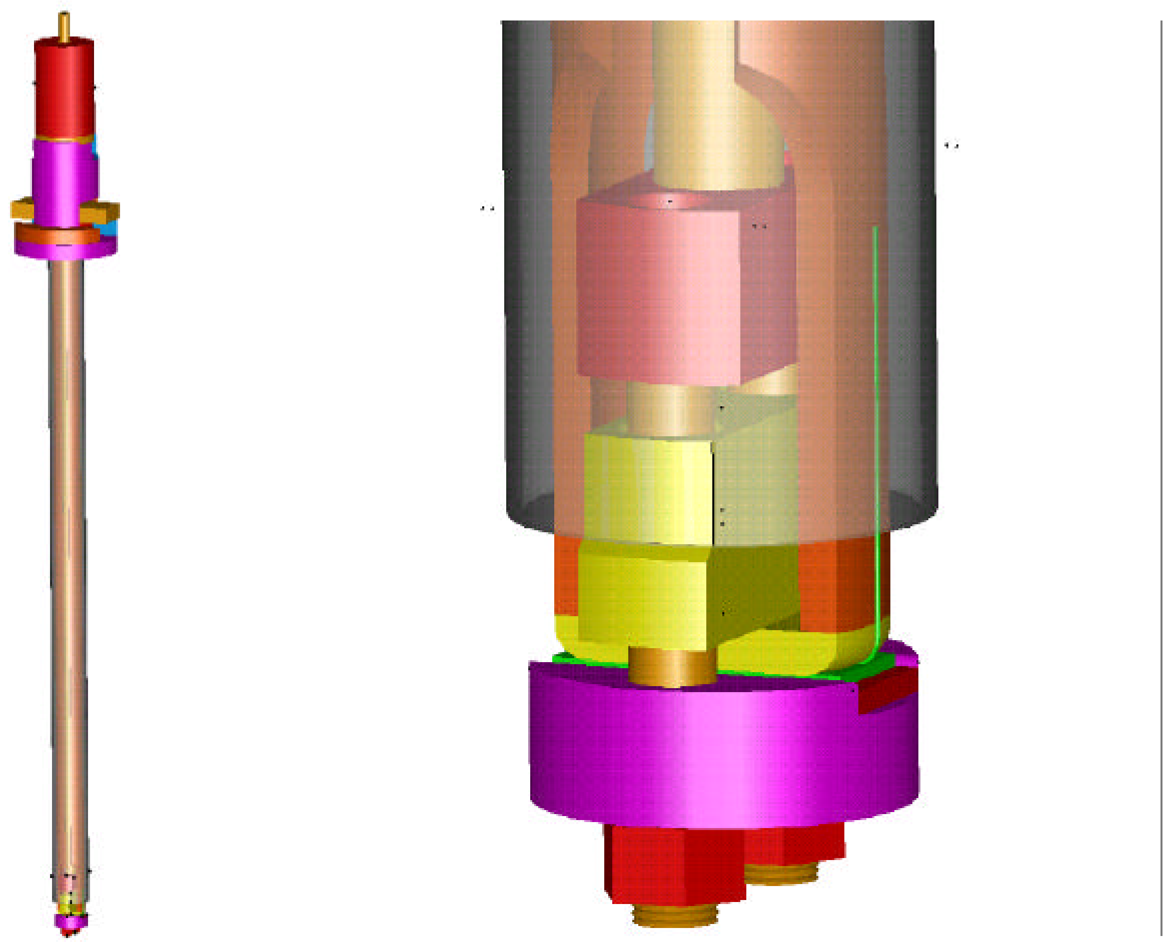

Figure 1. Conceptual design of the Cable/Strand Strain Test Fixture (C/SSTF).

The conceptual design is shown in Figure 1. The Nb_3Sn cable is compressed between two plates. The bottom plate is driven up by a rod assembly, which is pulled up by a 20 ton hydraulic cylinder placed on the top flange of the device. The top plate is welded to a tube, which is itself welded to the top flange of the device, which is fastened with screws to the existent facility.

Besides the previous specifications, the device had to meet three additional functional requirements:

- The length of the strand sample had to be long enough to ensure the transfer of current between the copper lead and the superconductor;
- The cable sample (brittle and strain sensitive after heat treatment) had to be carefully mounted at the bottom of the device, and the two strand ends had to be soldered to the copper leads;
- The differential thermal contraction between the copper and the structural material had to be taken into account to avoid thermal stress in the structure.

To meet these requests, the conceptual design was slightly modified, as shown in the assembly in Figure 2. The height of the top plate was increased as needed for the current transfer length, and the tube was shortened to allow soldering of the sample ends.

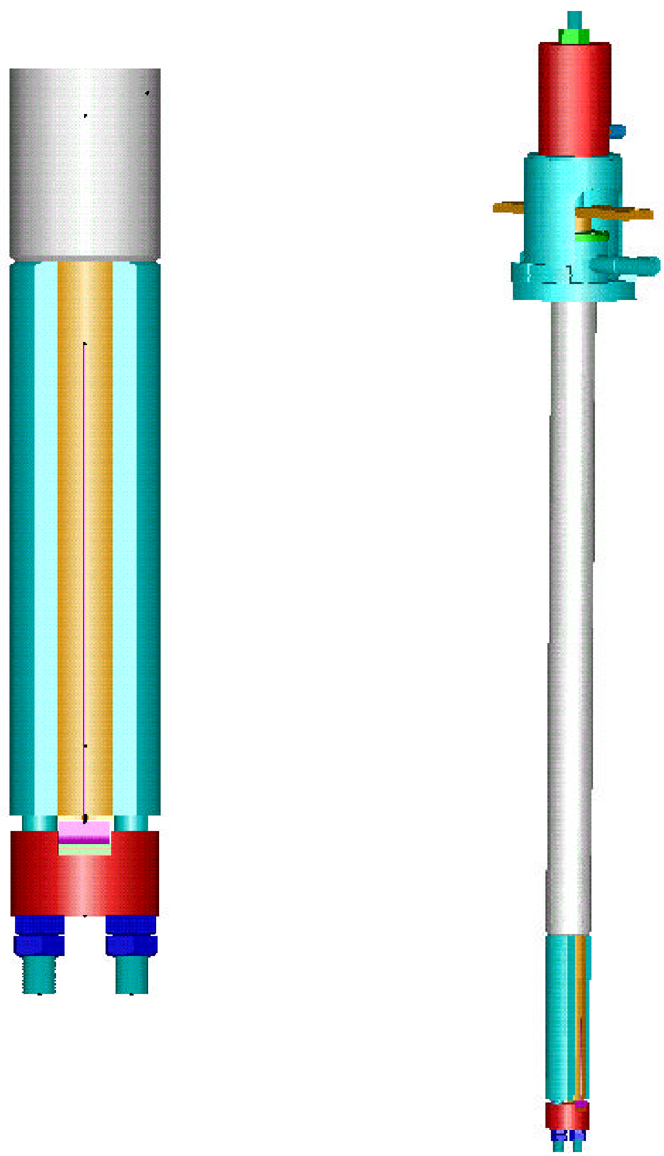

Figure 2. Fixture assembly design after mechanical and thermal analyses.

The third requirement was met by leaving the current leads free to move within the flange at the top of the assembly.

3. MECHANICAL DESIGN

The mechanical analysis was done in two steps. First, each component was sized analytically, then the final assembly was verified with ANSYS. This was done to check possible stress concentrations in the device. As a long beam under compression, the tube was also verified to instability. The sagitta of the two plates was also calculated. It was negligible in both cases. The results of the analytical calculations, detailed in Appendix A, are compared with ANSYS output in Table 1 below. A description of the ANSYS model that was used is given later in this section. From the results the following conclusions were derived:

- The high stress in the tube and in the rods requires complete joint penetration welds (CJP);
- Taking into account a safety factor of 1.3, the structural material must have a tensile yield strength greater than 1040 MPa.

For these reasons, Inconel 718, with a tensile yield strength of 1100 MPa, was chosen as structural material for the tube, the rod assembly and the plates, and as filler metal for the welds.

Item	Max s (MPa) Analytical	Max s (MPa) Ansys	Sagitta (mm) Analytical	Sagitta (mm) Ansys
Tube *	344	799	-	-
Large rod *	667	-	-	-
Small rod *	635	-	-	-
Top plate	460	398	~ 0	~ 0
Bottom plate	228	391	0.006	0.005

* CJP welds

Table 1. Comparison of the analytical results with ANSYS output.

The ANSYS model that was used is shown in Figure 3. Thanks to the axial symmetry of the structure and of the loads, a quarter only of the whole assembly was modeled. This included the tube, the top plate, the insulator, the cable sample and the bottom plate. A quarter of the 20 ton load was applied as a uniform pressure on the bottom plate in the contact area of the nuts, as shown in Figure 4.

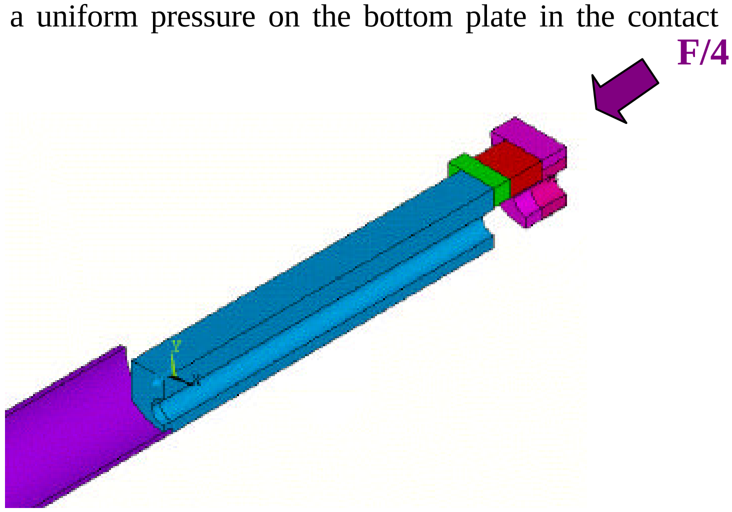

Figure 3. ANSYS model representing a quarter of the whole assembly. In Figure (from left to right), the purple part is the tube, the blue one is the top plate, the green block is the insulator, the red one is the cable, and the magenta one is the bottom plate. A quarter of the 20 ton load, F/4 in Figure, was applied to the bottom plate as described in more detail in Figure 4.

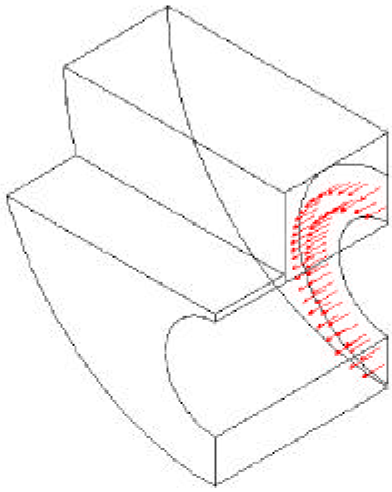

Figure 4. Load distribution on the bottom plate. The load was applied as a uniform pressure in the contact area with the nuts.

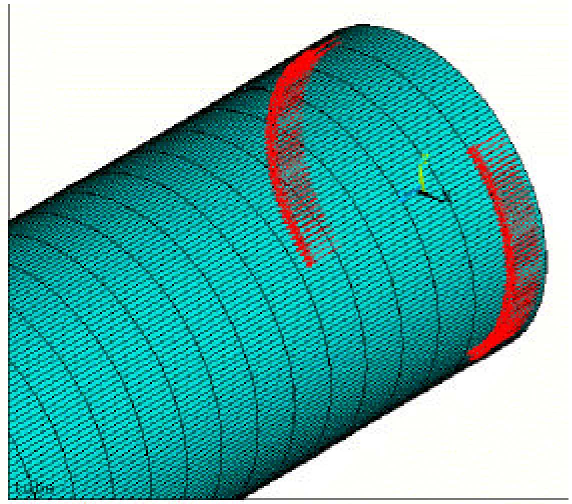

Figure 5. Load distribution and mesh of the single tube. The load was applied only at the nodes shared with the superior plate

The first analysis of the assembly gave a very high stress concentration in just one element of the tube, at the junction with the top plate. To check whether this was a spurious effect of meshing, the analysis was repeated with finer meshes. An exponential increase of stress concentration ensued that was therefore interpreted as a singularity. The tube was then analyzed individually. The load distribution and mesh for the single tube are shown in Figure 5. A detail of the stress distribution is shown in Figure 6. The maximum equivalent stress of about 800 MPa, located close to the top plate, was greater than that calculated analytically by a factor of 2.3.

Figure 7 represents the axial displacements of the bottom plate. The displacement distribution in the area of the sample location is very uniform, ensuring an adequate rigidity of the plate. The bottom plate sagitta calculated with ANSYS was of only 5 μm.

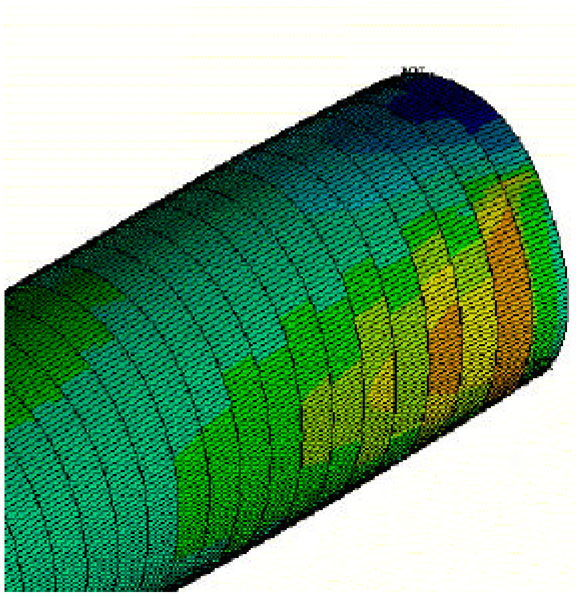

Figure 6. ANSYS results of the equivalent stress in the assembly. The red area bears a stress of about 800 MPa.

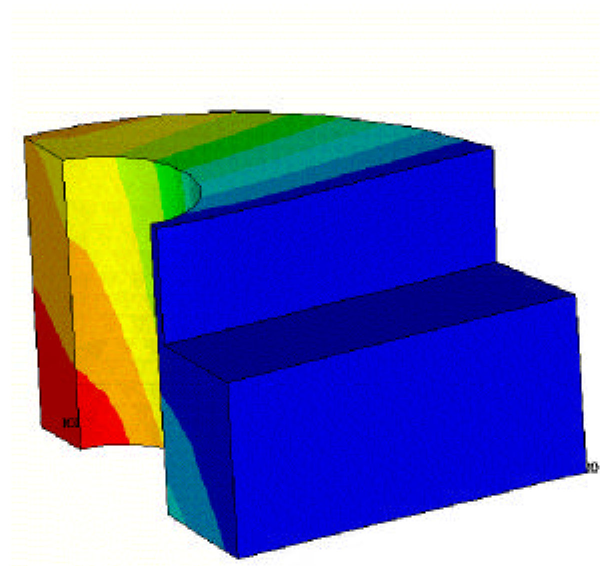

Figure 7. Axial displacements of the bottom plate. The uniform blue color in the area of the sample location ensures an adequate rigidity of the plate.

4. THERMAL DESIGN

Two different codes were available to size the current leads: LEAD created by M. Wake [6], and CCLAMP by Ruben Carcagno et al. [7]. The former, which is simpler to use, was chosen for dimensioning the leads. The latter, which allows more operating options, was used to compare the results of the two codes using the same initial conditions. Therefore, CCLAMP was run by fixing the temperature at the top of the leads, by deactivating the mass flow controller, and by considering a large difference between gas and copper temperature. The parameters used in both cases are listed in Table 2. The maximum temperature in the leads (Figure 7) and the He mass flow rate (Figure 8) were calculated as a function of the copper RRR.

Parameters (for the two leads)	
Length (m)	0.884
Perimeter (m)	0.13
Cu area (m^2)	0.0002
Gas area (m^2)	0.0007
Hydraulic diameter (m)	0.046
Warm end temperature (K)	300
Cold end temperature (K)	4.2
Current (A)	4000

Table 2. Parameter used in the two codes. These parameters are associated to both leads.

Comparing the results of both codes, LEAD appears to be more conservative than CCLAMP. This is why the leads were sized using the former. For both codes, the worst condition for the mass flow was for a copper with a RRR of 100. Using LEAD and a RRR of 100, the loss of He coolant was calculated to be about 0.3 liter per measurement for a measurement duration of 5 minutes.

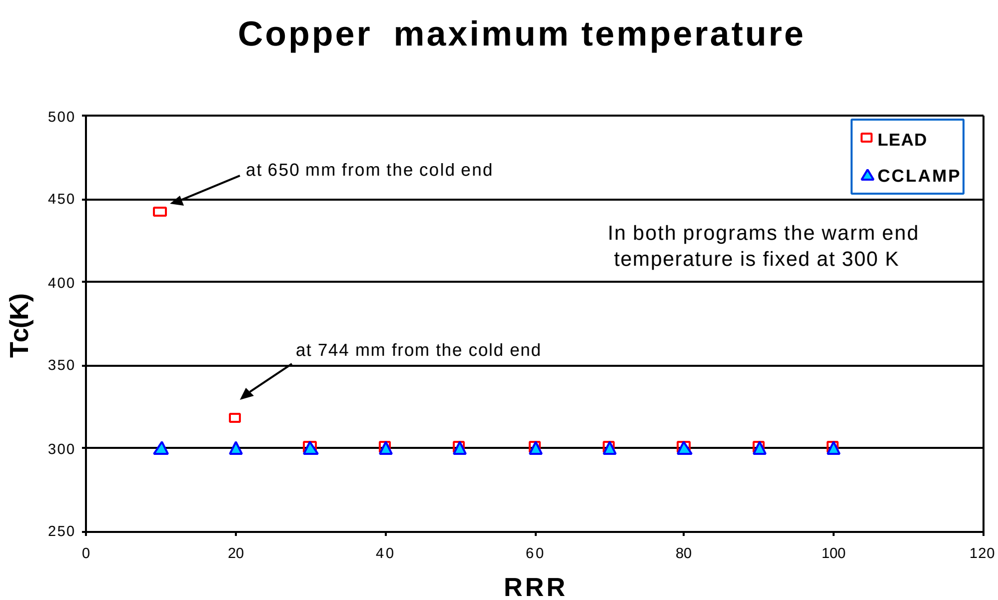

Figure 7. Maximum temperature reached by the leads as a function of the copper RRR calculated with LEAD and CCLAMP. Both codes give the same results for RRR's over 30.

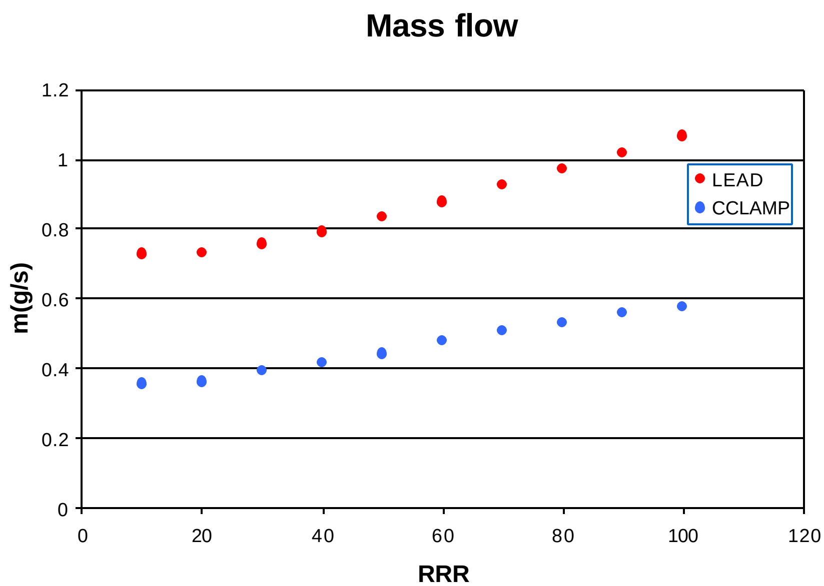

Figure 8. Mass flow rate calculated with LEAD and CCLAMP as a function of RRR.

Finally, CCLAMP was used to estimate the warm end temperature of the leads (Figure 9), in order to check whether they would freeze during the measurements. To be more realistic, the code was run by imposing a small difference between the He and the Cu temperatures. As is shown in the plot, the temperature of the leads should not go under 273 K and the leads are therefore not expected to freeze.

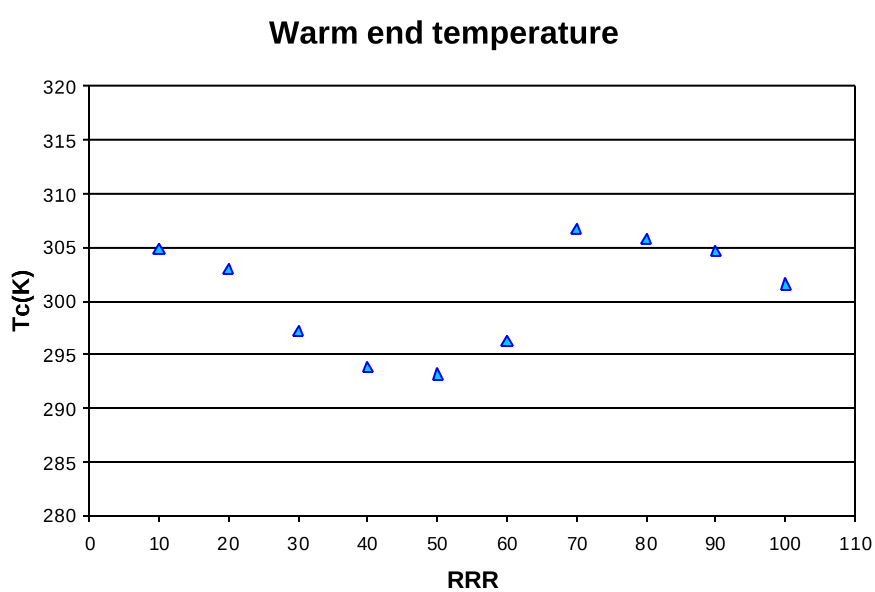

Figure 9. Lead warm end temperature, according to CCLAMP calculation.

5. SUMMARY

The Cable/Strand Strain Test Fixture (C/SSTF) was sized and analyzed under the mechanical and thermal points of view. Technical drawings are being presently released. Then parts procurement will start, followed by mounting and commissioning of the device. In the meantime, an impregnation fixture for the cable sample is being designed, as well as a procedure for sample handling.

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